Development and Testing of a Green-Propellant Micro-Hybrid Thruster with Electrostatic Ignition

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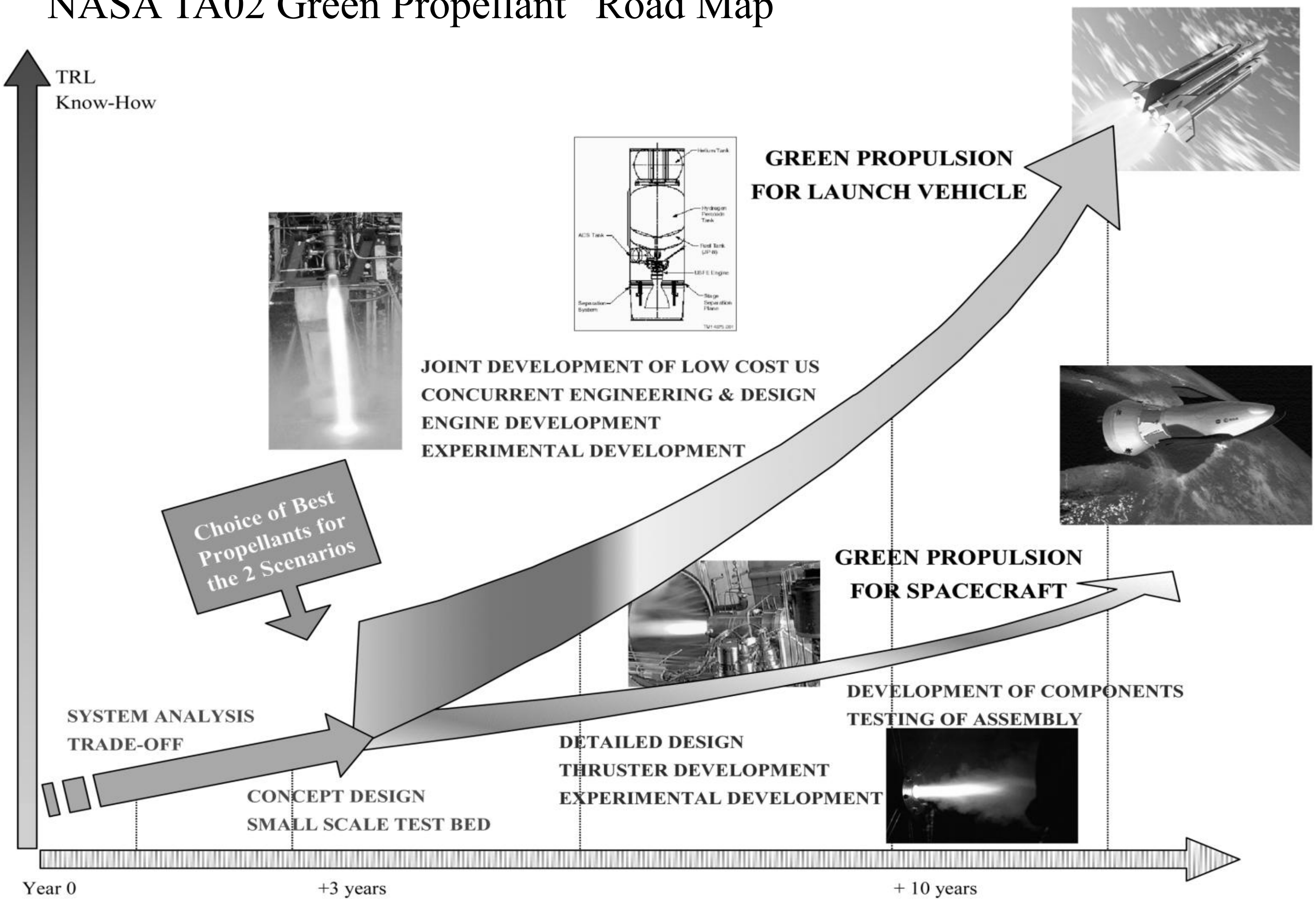
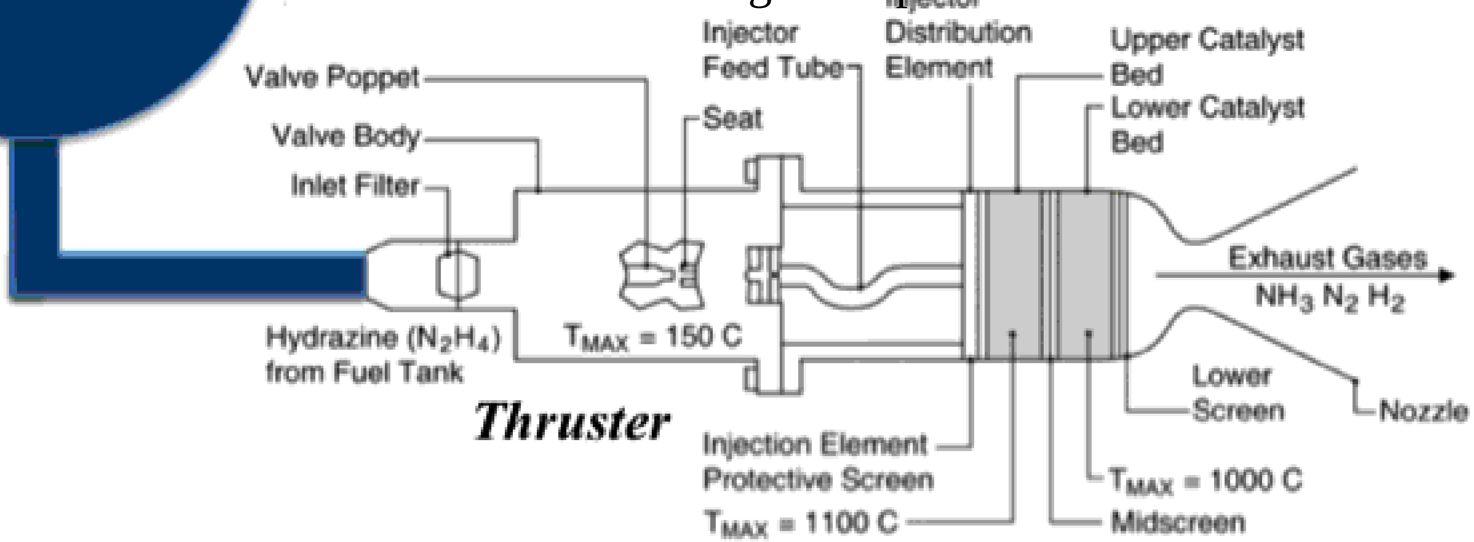
NASA TA02 Green Propellant "Road Map"



"Evaluate alternate green propellants that allow thrusters to operate in pulse and continuous modes with these new propellants. Qualify propellants, components (valves, filters, regulators etc) for spaceflight."

Hydrazine as the "Gold Standard" for In-Space Monopropellants

- **Hydrazine (N_2H_4) .. most commonly used space monopropellant for both primary and attitude control thrusters**
  - Well developed catalyst (S-405®), Highly reliable ignition
  - Simple system design
  - Highly exothermic decomposition
  - Moderate performance, I_{sp} >220 sec
  - Long term storable
  - High specific gravity, excellent volumetric efficiency
  - Cold-Start ignition possible



Operational Hazards of Working with Hydrazine

- **Unfortunately, Hydrazine also presents significant toxicity and physical hazards**
  - Highly energetic, anhydrous hydrazine can detonate from impact
  - Low explosive flaspoint at 38 C.
  - Highly toxic, both a reducing agent and oxidizer, corrosive to living tissue
  - Extreme vapor hazard, service and inspection operations require S.C.A.P.E suits
  - Known carcinogen for both short and long-term exposure.
  - Recommended safe levels for hydrazine's carcinogenic properties are far lower than those of biological effects stemming from chemical properties.

- **European Space Agency/European Space Research and Technology Center (*ESA/ESTEC*) study (2003)**
  - Significant potential cost savings by *reducing propellant production, operational, and transport costs due to lower propellant toxicity and explosion hazard*
  - Operational complexities of dealing with hazardous propellants especially expensive for emerging private-space corporations.
  - Less toxic, moderate performance hydrazine mono-propellant replacements highly desirable.

Bombelli, V., "Economic Benefits for the Use of Non-toxic Monopropellants for Spacecraft Applications, AIAA-2003-4783, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, AL, July 2003.

Hydrazine Replacement Alternatives

- **Desired Characteristics**
  - Long term storable,
  - Low freezing point
  - Moderate combustion temperature, but high hydrogen content (low molecular weight) for high I_{sp}
  - High density for volumetric efficiency
  - High vapor pressure for self-pressurization
  - Reduced or low toxicity
  - Chemically and thermally stable to prevent detonation hazard
  - Must possess a relatively low activation energy for easy and reliable ignition
- **Last two items in above list are in direct conflict and must be traded-off**
- **If vapors are toxic or corrosive, high vapor pressure propellant can present significant respiratory hazard**
- **Potential Candidates as Alternatives to Hydrazine**
  - *Hydrogen Peroxide,* H_2O_2
  - *Hydroxethylhydrazine* ($C_2H_8N_2O$)
  - *Nitrous Oxide Fuel Blends, NOFBx, NOOLMR*
  - *Nitrous Oxide monopropellant,* N_2O
  - Ionic Liquids (in aqueous solution)

    Ammonium DiNitramide (ADN), HPGP, LMP 103s

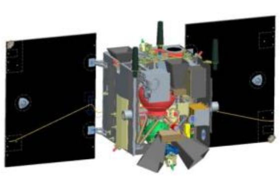
    Hydroxylamine Nitrate (HAN), XM 1846, HANGLY26, HAN269MEO

Hydrazine Replacement Alternatives (2)

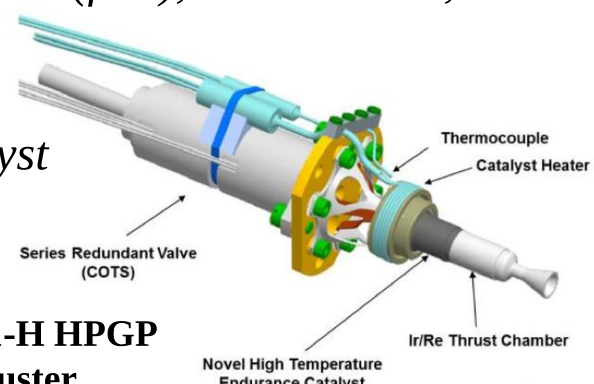
- **Hydrogen Peroxide (H_2O_2)**
  - Reduced toxicity compared to hydrazine but still toxic, corrosive
  - High room temperature vapor pressure, significant vapor hazard
  - Low specific impulse compared to hydrazine < 180 C
  - Not really a *"green propellant"*
- **Hydroxethylhydrazine ($C_2H_8N_2O$)**
  - "Less toxic" monopropellant being developed by USAF
  - 50% improvement in density specific impulse compared to hydrazine
  - Most information is classified, assume low current TRL
  - Not truly a "green propellant
- **Nitrous Oxide Fuel Blends**
  - $NOFB_X$ emulsion of nitrous oxide and hydrogen gas
  - I_{sp} > 300 sec, cleared for test on ISS
  - Currently DOT 1.1 explosive, not cleared for commercial transport by DOT
- **NOOLMR**
  - N_2O, ethanol proprietary mix, Low TRL no commercial product available
- **Nitrous Oxide monopropellant**
  - Catalytic decomposition, no reusable catalyst, *low I_{sp} < 170 seconds.*

Hydrazine Replacement Alternatives (3)

- **"Ionic Liquids" .. Ammonium salts that melt below boiling point of water**
  - **Ammonium DiNitramide (ADN, $NH_4(NO_2)_2N$) acts as oxidizer**
    - ECAPS LMP-103s High Performance Green Propellant (HPGP)
    - 60-65% ADN, 15-20% methanol (C_4HO), 3-6% Ammonia (NH_3), and 9-22% water
    - Catalytically decomposed, products H_2O vapor, N_2, O_2, and 2000 kJ/kg heat
    - High specific impulse potential > 230 sec vacuum
    - ESA Prisma flight demo, 1 N thruster flown as experiment not primary propulsion
    - Proprietary high temperature catalyst, requires 30 minute preheat at 8.5 W.
  - **Hydroxylammonium Nitrate (HAN) acts as oxidizer**
    - *US Army LP 1846 (XM 46), 60.8% HAN, 19.2%* tri-ethanol-ammonium nitrate (TEAN, fuel), 20% Water.
      - *Originally developed as monopropellant for artillery*
    - *Aerojet HANGLY26*, 60% HAN, 14% Glycine (fuel), 26% Water.
    - *Aerojet HAN269MEO, 69.7% HAN, 14.8% Methanol (fuel), 14.9% Water, 0.6% Ammonium Nitrate (stabilizer)*
    - *HanGLY26* → I_{sp} *~ 190 sec*
    - *HAN269MEO* → I_{sp} *~ 270 sec, No reusable catalyst*



Prisma "Mango" Spacecraft



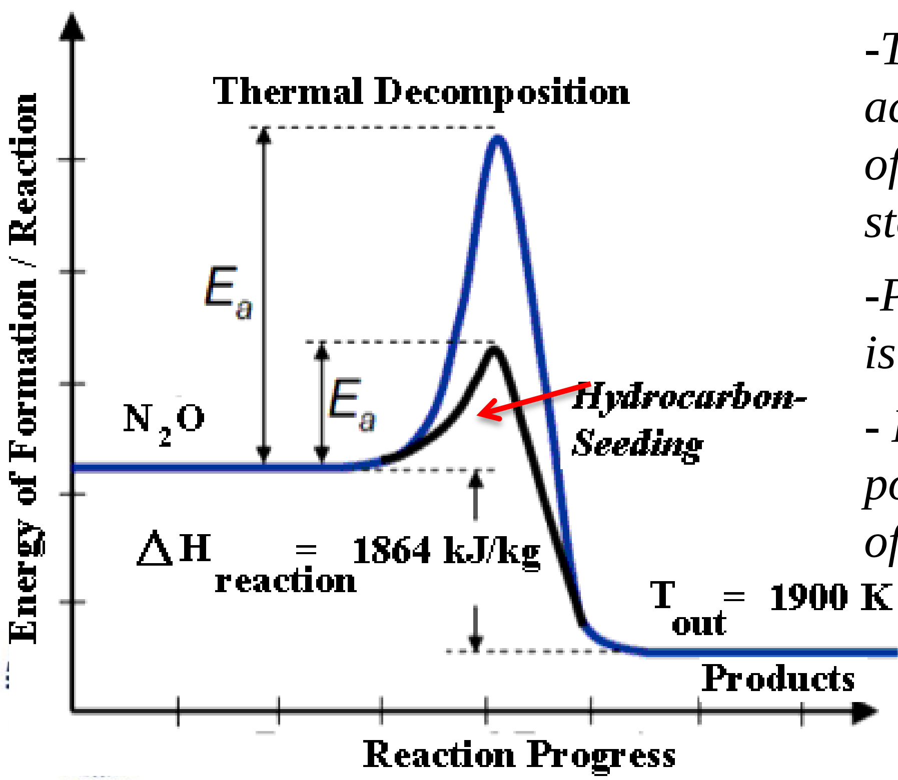
ECAPS 1-H HPGP Thruster

Hydrazine Replacement Alternatives (4)

- **Ionic Liquid (IL)-Based monopropellants**
  - All propellant formulations using IL are considerably denser than hydrazine, producing a significant improvement in volumetric efficiency
  - Ammonium salts are high energetic, and can be subject to rapid, uncontrolled decomposition
  - Explosion potential buffered by working with aqueous solutions
  - Hanford and Savannah River nuclear site explosions caused by low water content HAN solution being used for equipment decontamination
- **Ignition of IL-based monopropellants**
  - High water content IL-solutions are safer to handle, but notoriously hard to ignite
  - IL-water binary solutions can be thermally dissociated at temperatures between 130-180 C
  - Fuel component significantly increases required dissociation temperature > 350 C
  - Catalytic decomposition is method of choice
  - Once ignited propellants burn significantly hotter than hydrazine ~ 1350-1700 C
  - Catalyst bed survivability is a large issue
  - *"Cold-start" catalyst does not exist for IL/fuel propellants. The catalyst bed must be pre-heated to greater than 350 C before firing*
    - *Significant electrical power required*
    - *ECAPS 1-N Prisma thruster >15 kJ preheat energy consumed*
    - *Significant liability for space propulsion where "on demand" ignition is desired.*

Hydrocarbon Seeded Hybrid Combustion

- **This approach "borrows" from basic premise of NOFBx, and NOOLMR propellants**
  - When relatively stable liquid oxidizer like Nitrous Oxide is mixed with a small amount of a soluble fuel like alcohol or GH_2, the mixtures are capable of producing significantly higher specific impulse than existing monopropellants > 300 sec.
  - The resulting mixture also has a significantly reduced thermal and impact stability
    - *Recent work by Karabeyoglu et al. has demonstrated the extreme risks of mixing liquid fuel components with liquid nitrous oxide.*



-Tragic July, 2007 Scaled-Composites, Inc. accident in Mojave California was a direct result of hydrocarbon contamination of N_2O oxidizer storage tank.

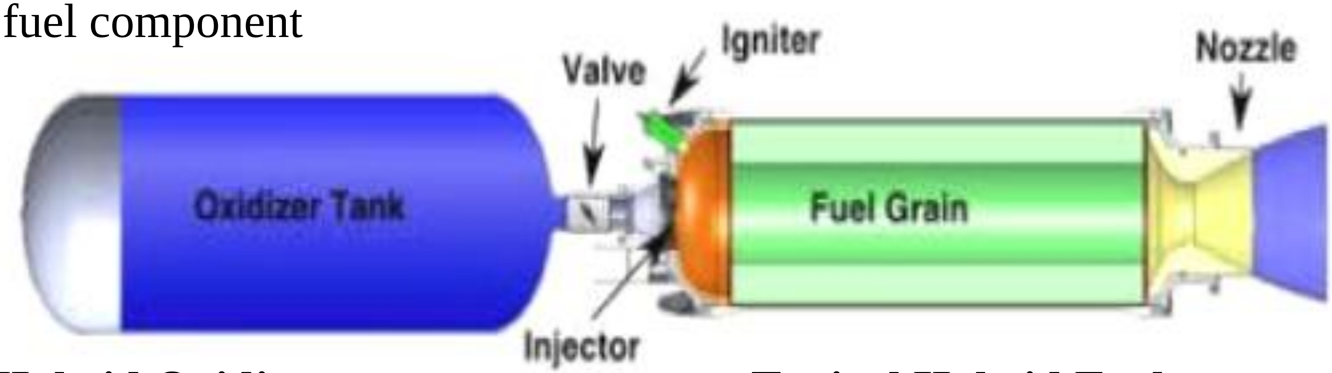
-Performance and safety under zero-g conditions is unknown

- Proposed approach mitigates the explosion potential of liquid fuel blends by using the theory of operation of hybrid rockets

Karabeyoglu, A., Dyer, J., Stevens, J., and Cantwell, B., Modeling of N2O Decomposition Events, AIAA 2008-4933, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Hartford CT, July 30-Aug 2, 2008

Hydrocarbon Seeded Hybrid Combustion (2)

- **Hybrid Rockets**
  - Liquid oxidizer is stored separately from (Typically) inert solid fuel
  - Relatively Stability and inherent-safety of hybrid rockets is well known
  - Propellants are mixed only within combustor as external ignition source ablates the solid fuel component



- **Typical Hybrid Oxidizers**
  - LOX (O_2)
    - … *Higher I_{sp}, dangerous to handle*
    - … *Limited Storability*
  - Nitrous Oxide ($N_2 0$)
    - … Lower I_{sp}, safe for handling
    - … highly storable
  - Hydrogen Peroxide (H_2O_2)
    - … Highest effective hybrid I_{sp},
    - … Highly storable
    - … Very toxic, *"Not green"*

- **Typical Hybrid Fuels**
  - Hydroxy-terminated polybutadiene (HTPB)
  - Plexiglass --polymethly-methacrylate – (PMMA)
  - Polyvinyl Chloride (PVC)
  - Acrylonitrile-Butadiene-Styrene (ABS)

Hydrocarbon Seeded Hybrid Combustion (3)

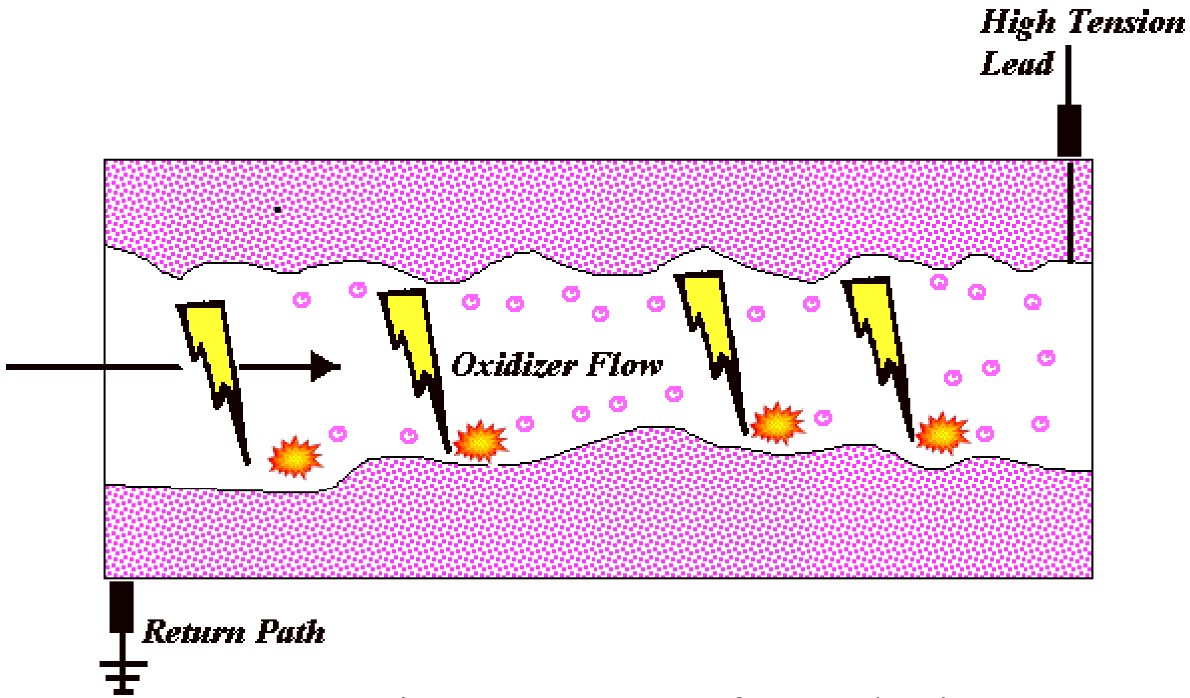
• **Heats of Ablation for Hybrid fuel grains are typically very high**

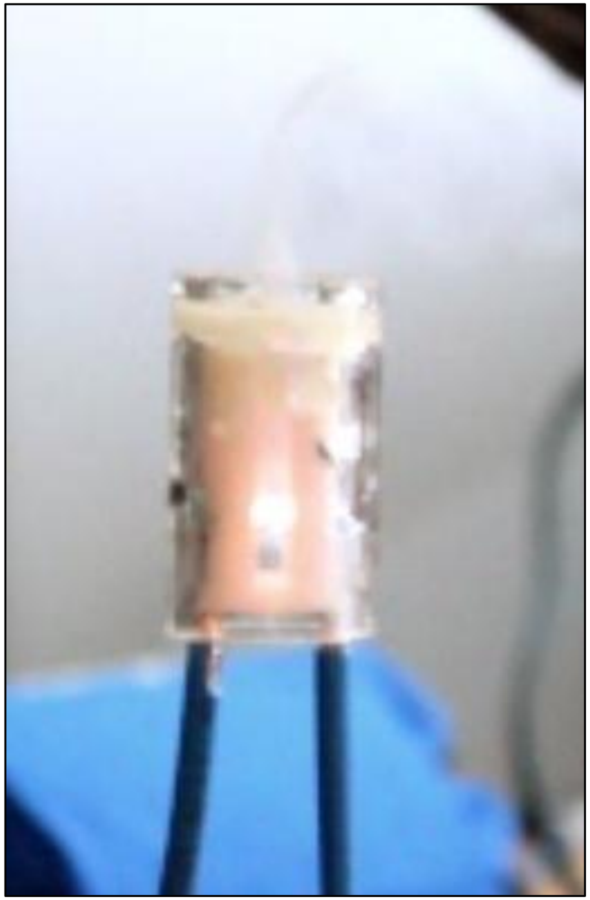
- *HPTB* $J_{ablation} > 1.8\ MJ$
- Like solid-propellant rockets, hybrid rockets are typically ignited using one or more pyrotechnic charges
- Pyrotechnic charges, although effective, are one-shot devices
- Highly vulnerable to hazards of electromagnetic radiation to ordnance (HERO)
- Alternate non–pyrotechnic ignition method highly desirable

• **Proposed innovation uses unique ABS properties to ignite hybrid device electrostatically**

- *ABS* plastic has a very high dielectric strength, *53.1 kV/mm*
- Small segment of *ABS* material possesses very high current impedance Allowing significant power to be dissipated before the material breaks down.
- When a high voltage is applied, charge buildup electrifies the grain until a spark jumps the gap across the fuel port, and locally between micro-ridges along the grain surface.
- Spark vaporizes small amount of material locally
- Residual spark energy triggers local reaction between ablated fuel and oxidizer flow
- Localized reaction triggers full-length port combustion

Hydrocarbon Seeded Hybrid Combustion (4)

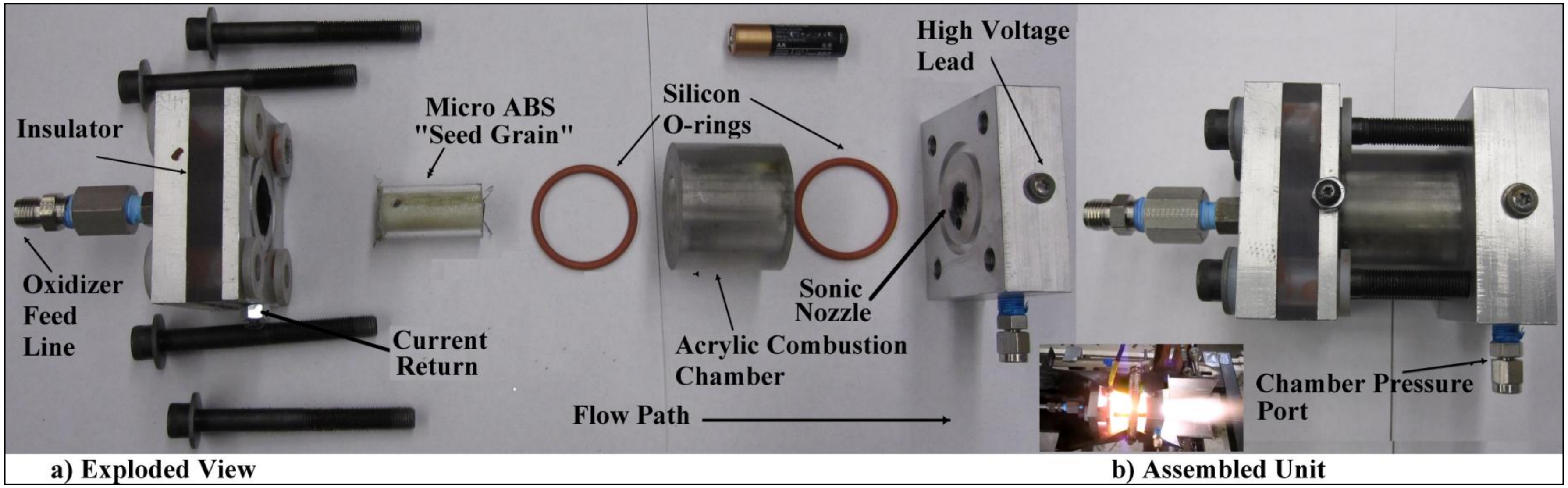




• ABS grain segment manufactured using Fused Deposition Model Rapid Prototyping Machine

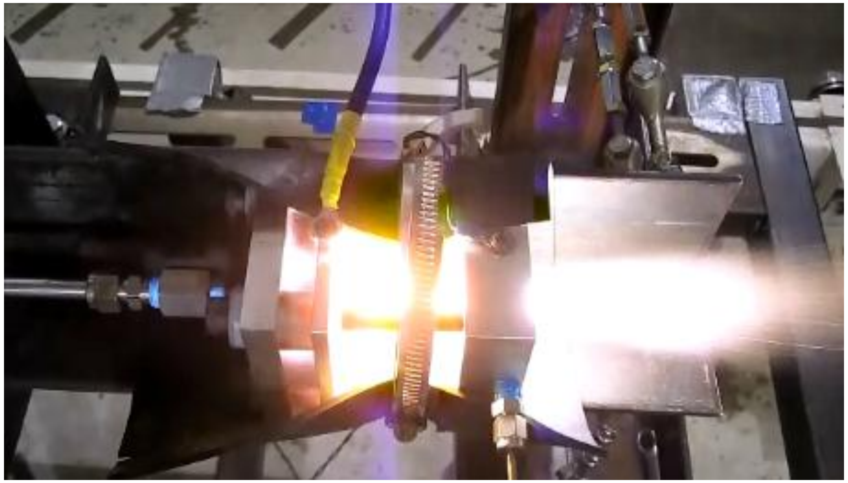
• Grain designed for "visibility," compactness

Prototype Hydrocarbon-Seeded Thruster



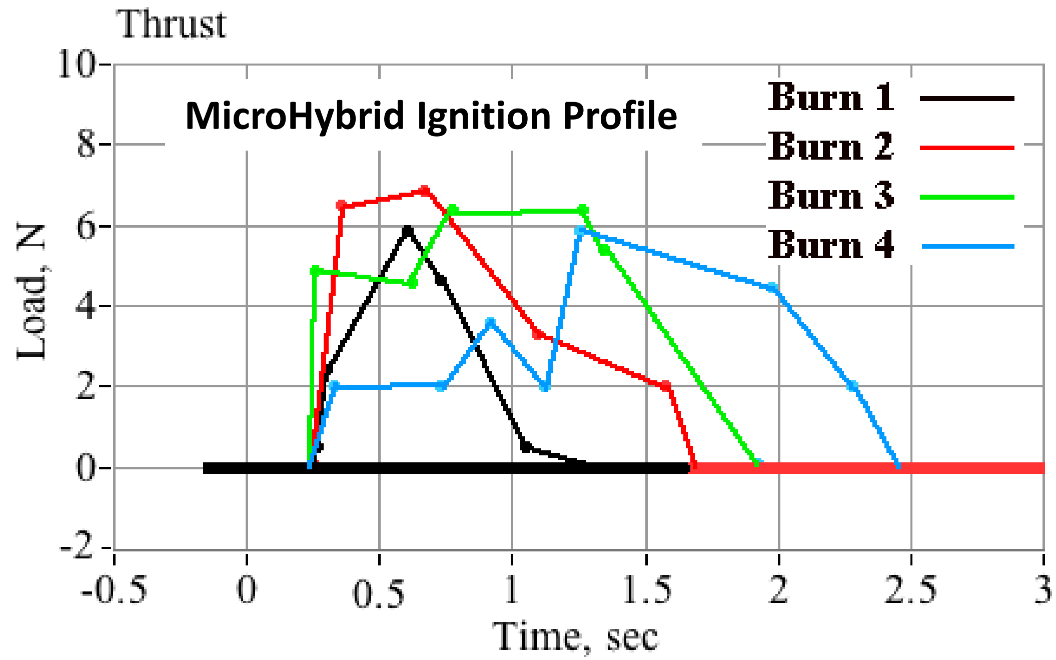
a) Exploded View b) Assembled Unit

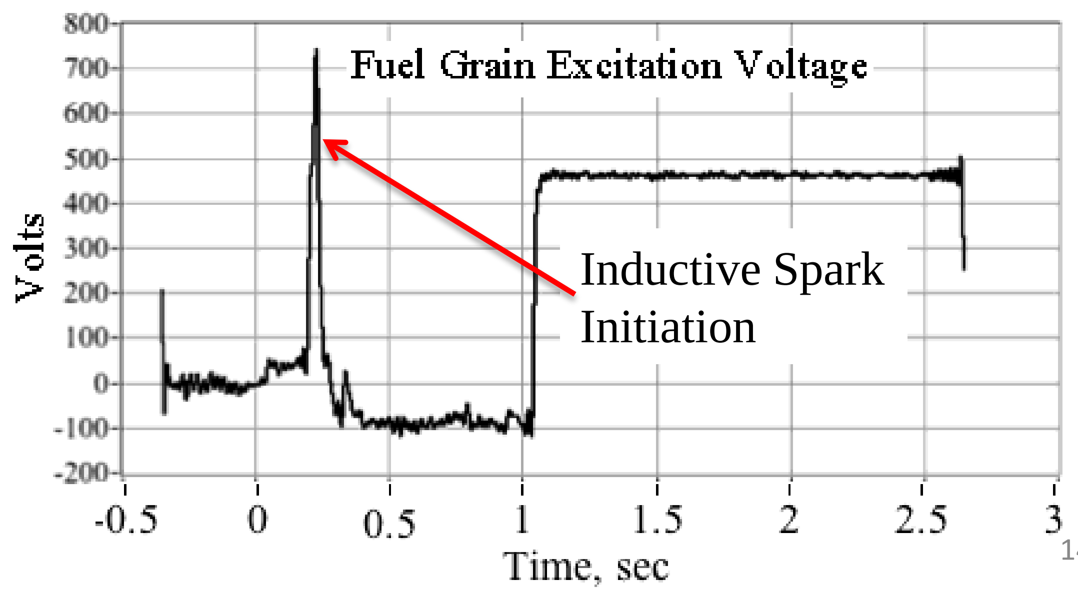
- Original design used a commercial TASER "stun gun"
- Current arc across grain segments
- Later design replaced TASER with Precision, High Voltage, Current Limited Power Supply
- Reversed current flow path (downstream to upstream) to move high tension lead away From Oxidizer inlet



Prototype Hydrocarbon-Seeded Thruster (2)

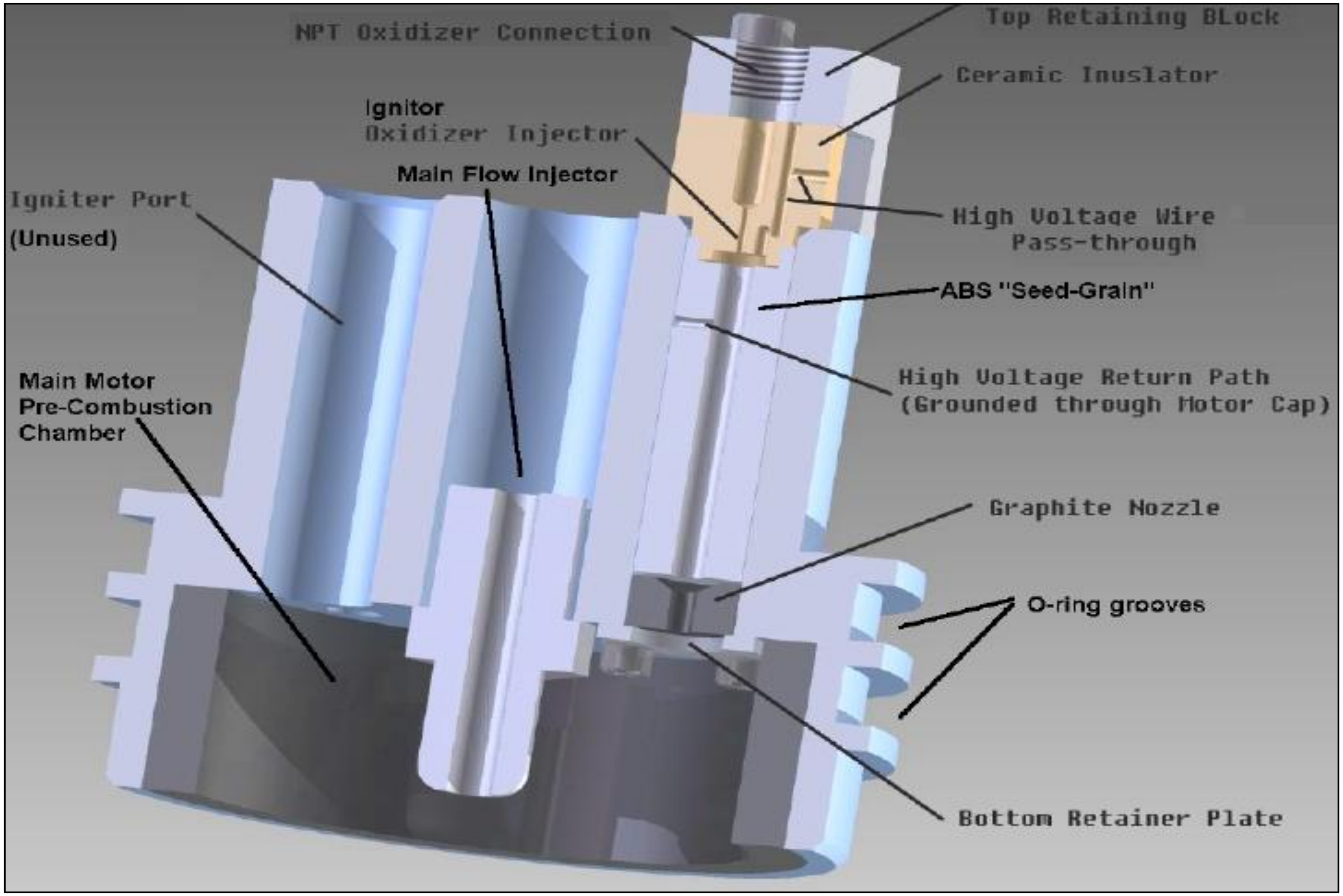
- Electrical charge precedes oxidizer valve opening by 0.25 sec
- 0.5-sec Oxidizer Pulse
- Approximately 7 N peak thrust
- 750 V Peak, 13 mA Current Limit, Total Ignition Energy < 2 J
- Repeatable ignition profile
- Burn tail-off duration increases as grain chars, and port diameter opens up



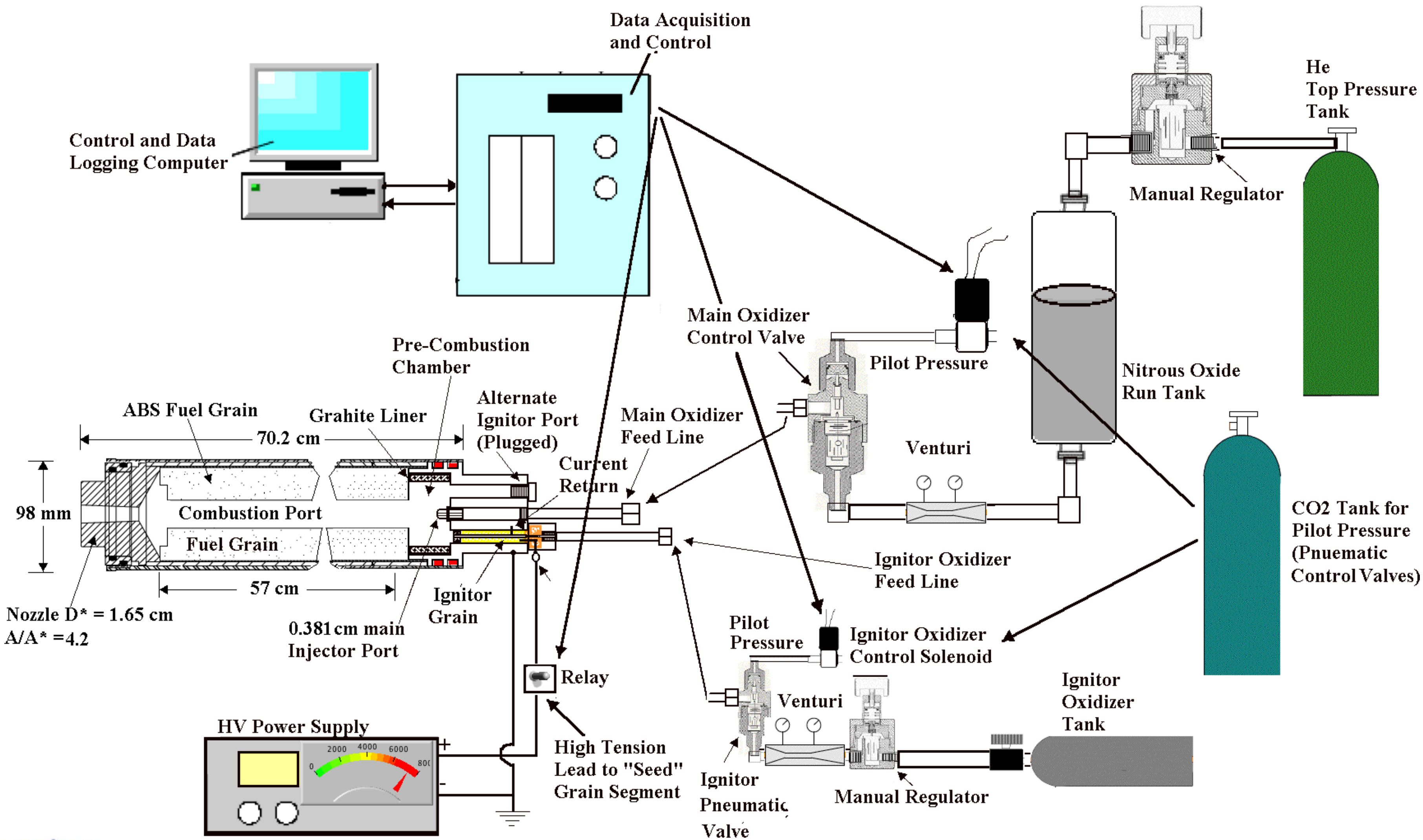


Prototype Hydrocarbon-Seeded Ignitor

- Micro-hybrid as non pyrotechnic ignitor for larger-scale 98 mm hybrid motor
- Main Motor propellants N_2O/HTPB
- Ignitor propellants GOX/ABS
- Up to 4-consecutive relights of main motor

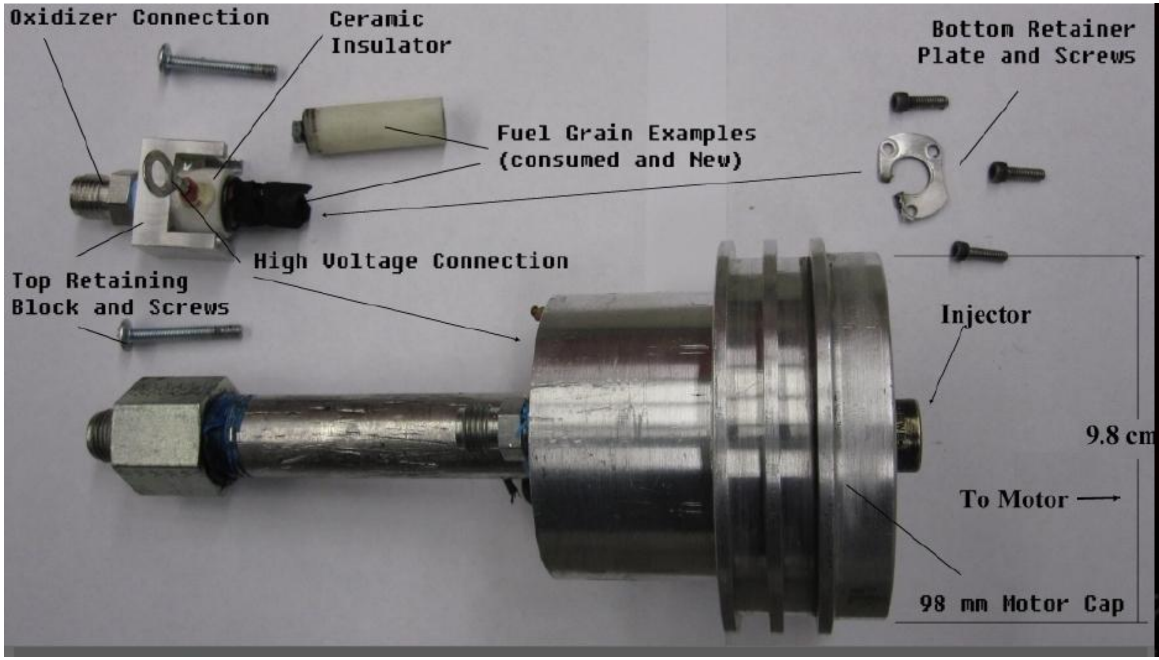


Prototype Hydrocarbon-Seeded Ignitor (2)



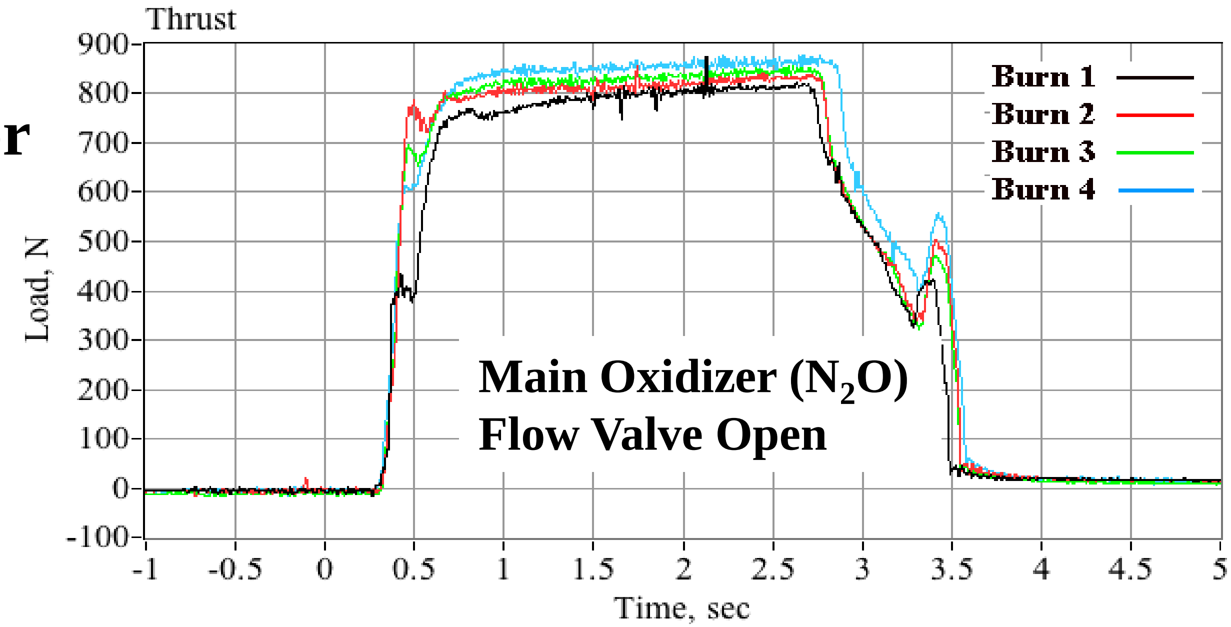
Experimental Apparatus Setup

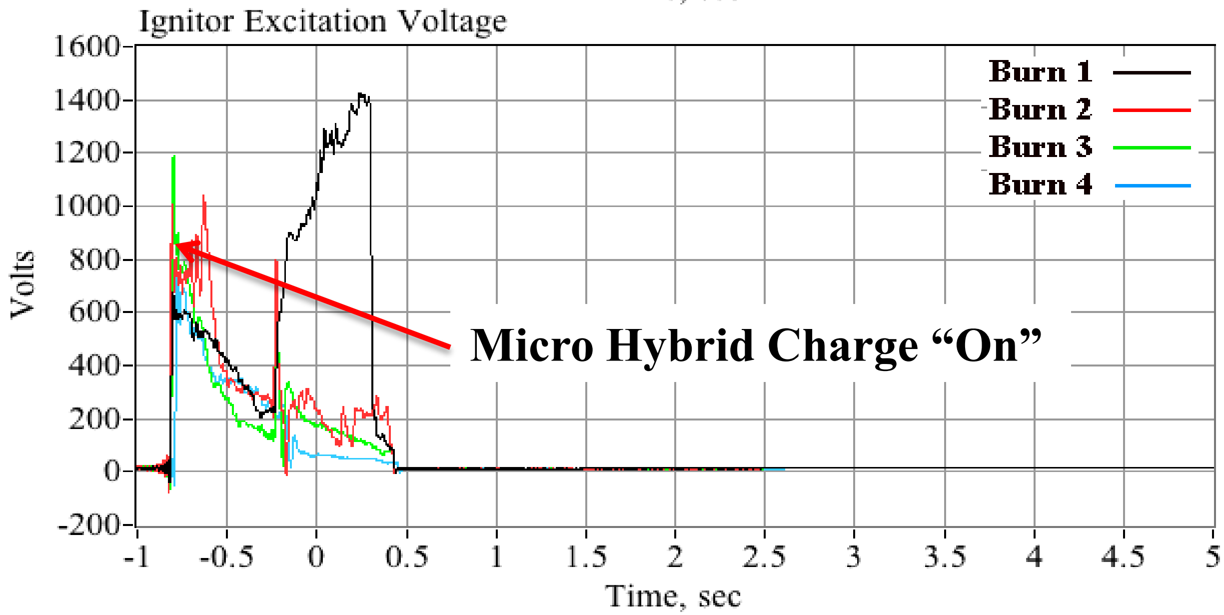
Prototype Hydrocarbon-Seeded Ignitor (3)



Prototype Hydrocarbon-Seeded Ignitor (4)

- 98mm Hybrid with Micro-Hybrid Ignitor
- Ignition and Burn Profile comparison
- Initial burn takes Considerably higher Startup energy
- After initial ABS grain char, burn profiles very similar





Alternative Oxidizer Options for Hydrocarbon-Seeded Hybrid

- ***Low-energy,*** Electrostatic-spark Hydrocarbon-seeded ignition proven viable for GOX
- ***Gaseous Oxygen,*** even at high pressures, has low density, poor volumetric efficiency
- ***Alternative,*** higher specific gravity, storable, "Green" oxidizers compatible with Hydrocarbon-seeding process highly desirable
- ***Potential Alternatives:*** Nitrous Oxide, Ionic Liquid Solutions

- **Nitrous Oxide Dissociation Reaction:**
  - Significantly higher chamber pressure or significantly higher energy "spark" required to initiate hydrocarbon-seeded combustion with nitrous oxide as oxidizer
  - Thermal decomposition requires heating vapor to a minimum of 800 C.
  - At lower pressures, thermal decomposition initially leans towards the endothermic reaction

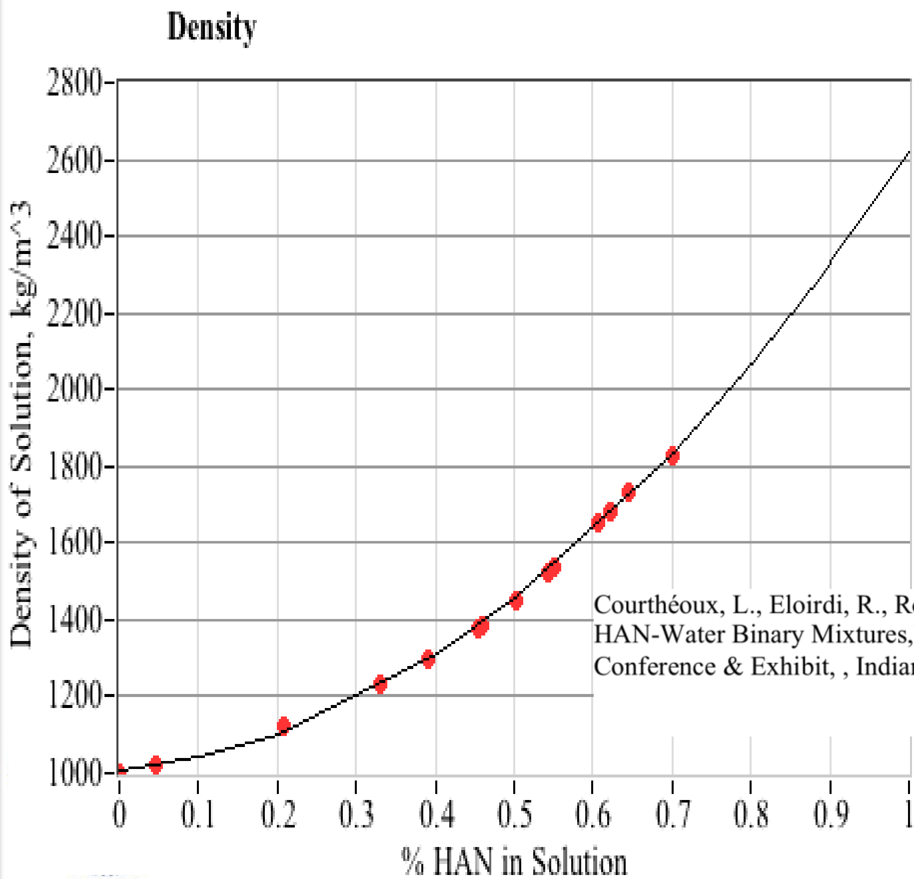
$$2N_2O \rightarrow 2NO + N_2$$

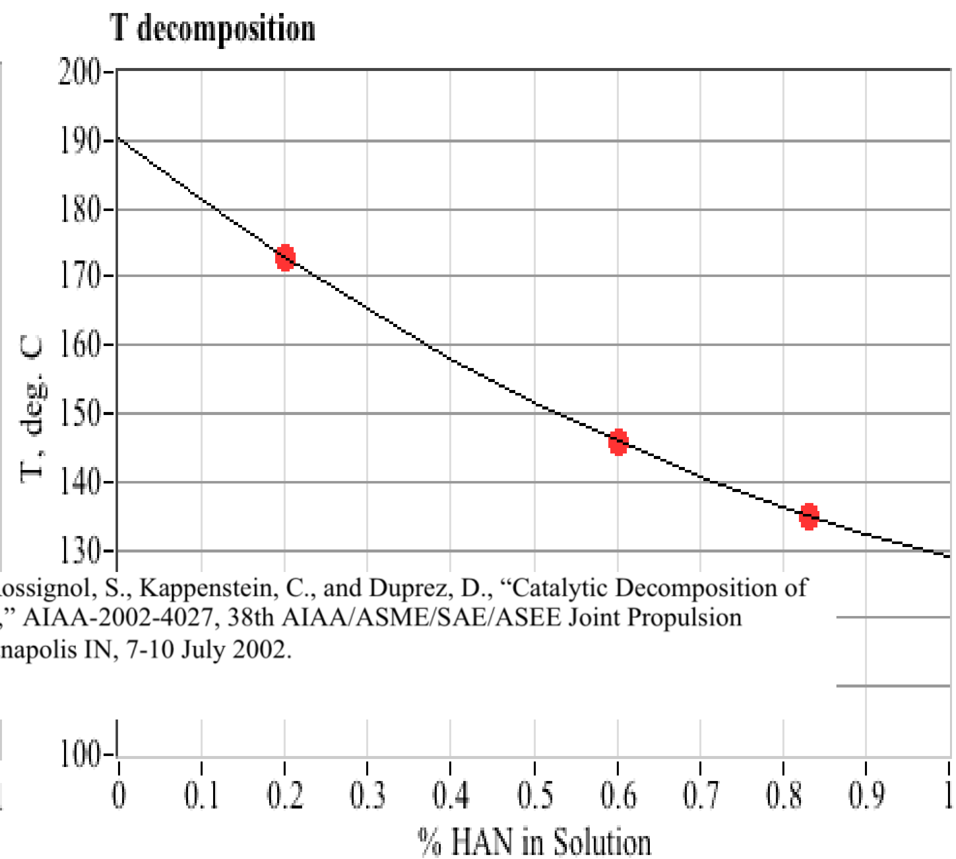
  - Endothermic reaction initially absorbs residual spark energy, sustained voltage input required to initiate exothermic reaction required for combustion

$$N_2O \rightarrow N_2 + \tfrac{1}{2}O_2$$

Alternative Oxidizer Options for Hydrocarbon-Seeded Hybrid (2)

- **Ionic Liquid Decomposition:**
  - Binary mixtures of IL's and water dissociate at considerably lower temperatures than nitrous oxide.
  - IL/water mixtures are also significantly more dense than nitrous oxide
  - *Note at Room Temperature nitrous density is ~ 780 kg/m*^{3}

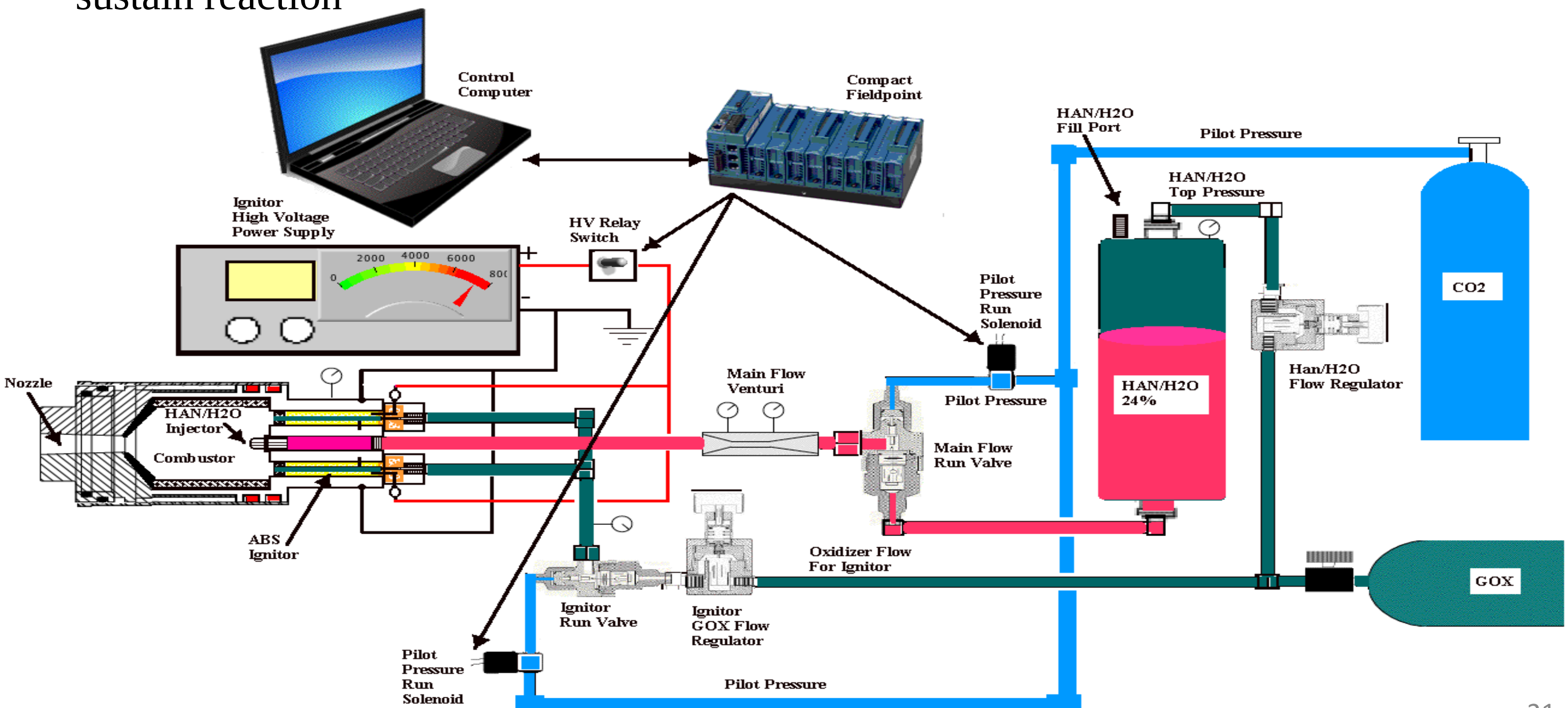




Courthéoux, L., Eloirdi, R., Rossignol, S., Kappenstein, C., and Duprez, D., "Catalytic Decomposition of HAN-Water Binary Mixtures," AIAA-2002-4027, 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, , Indianapolis IN, 7-10 July 2002.

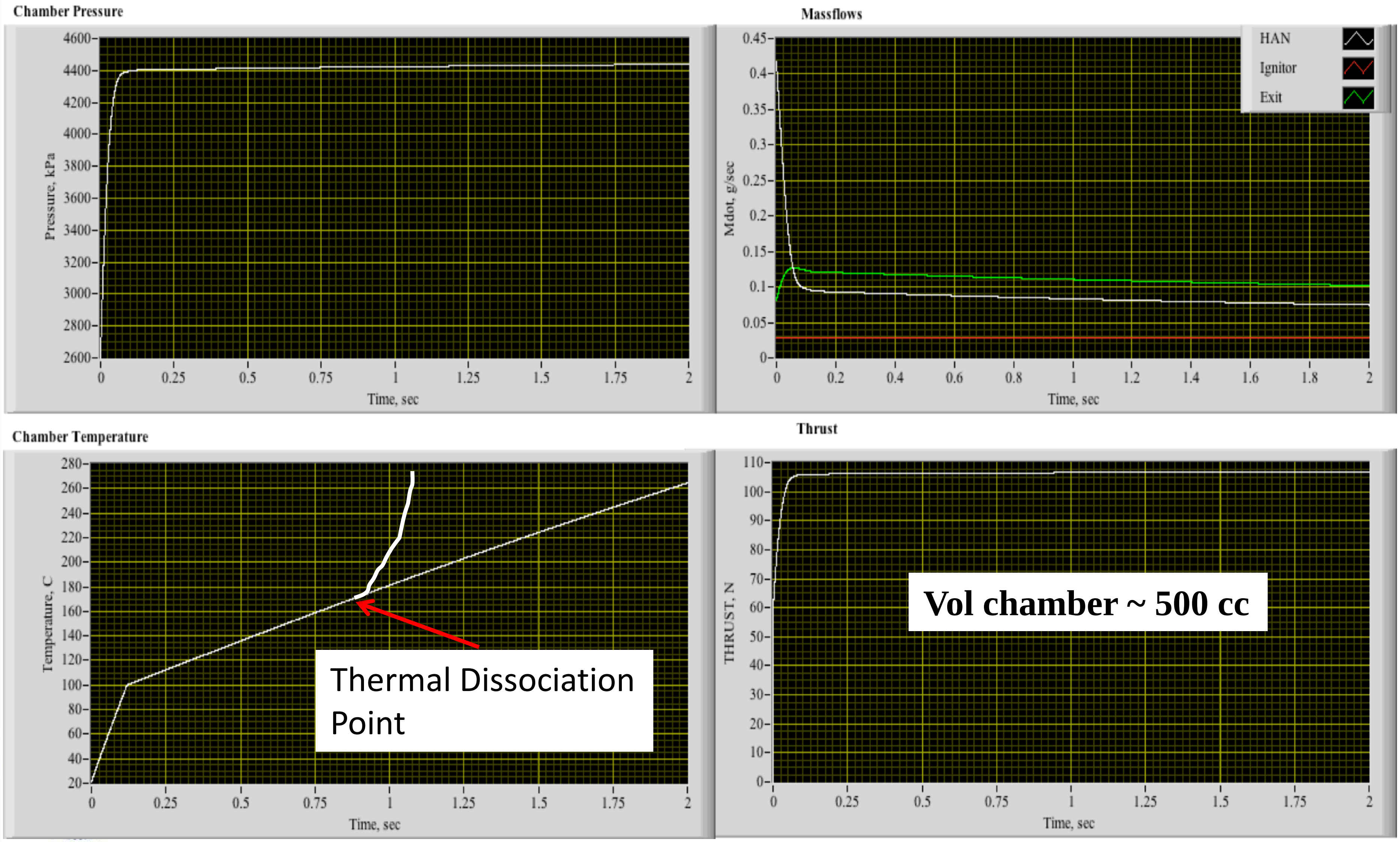
Alternative Oxidizer Options for Hydrocarbon-Seeded Hybrid (3)

- **Ionic Liquid Decomposition:**
  - Binary mixtures of IL's and water dissociate primarily once all water has vaporized and IL molecules can come into close contact.
  - Proposed experiment, use Micro-hybrid ignitors to heat 24% HAN solution to greater than 170 C to initiate thermal decomposition
  - Once thermal decomposition occurs, heat of decomposition >1600 KJ/kg should sustain reaction



Alternative Oxidizer Options for Hydrocarbon-Seeded Hybrid (4)

- **Homogeneous Vapor Simulation results:**



Conclusion

1. Demonstrated viability of initiating combustion on micro-hybrid using hydrocarbon-seeding is a significant step forward.
2. This approach allows the simplicity of mono-propellant ignition system, while still providing the high-energy and performance of a bi-propellant ignition system. *Vacuum I_{sp} > 270 sec demonstrated for N_2O/ABS hybrid*
3. The propellants, GOX and ABS are 100% non-toxic, inert, and environmentally benign.
4. Non-pyrotechnic ignition requires < 2 Joules, no propellant or catalyst preheat
5. Low ignition latency, multiple ignition capability
6. Approach to motor ignition highly resistant to Hazards of Electromagnetic Radiation to Ordnance (HERO).
7. Small ABS fuel segments used to "catalyze" the flow can be quickly and inexpensively fabricated using FDM rapid-prototyping machines
8. Grain designs can be easily "optimized" by redrawing grain CAD file

Conclusion (2)

9. Technology applicable to wide range of gas-generation systems where aqueous HAN or AND solutions replace hydrazine as the working fluid.
10. Because the aqueous ADN or HAN solutions have significantly higher densities than hydrazine, this application would offer significantly longer run-times or reduced overall system volumes.
11. By varying the HAN concentration within the mixture, the exhaust gas temperature can be moderated to insure a trade-off between ignition reliability and downstream component survivability.
12. Proposed experiment (to be performed this year) will use micro-hybrid ignitors to demonstrate feasibility to dissociate 24% HAN/water binary solution
13. 24% *HAN* solution highest commercially available concentration that can be shipped as non-hazardous material using conventional freight. If 24% solution can be thermally dissociated, very likely that aqueous solutions with a higher *HAN* concentration or *HAN/water/fuel* mixtures will also be ignited using hydrocarbon seeded ignition system.